Renewable and Sustainable Energy Reviews 189 (2024) 113938

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Critical mineral demand estimates for low-carbon technologies: What do they tell us and how can they evolve?

J.L. Calderon [a,*], N.M. Smith [a], M.D. Bazilian [b], E. Holley [a]

[a] Mining Engineering Department, Colorado School of Mines, CO, USA
[b] Payne Institute for Public Policy, Colorado School of Mines, CO, USA

ARTICLE INFO

Keywords:
Critical minerals
Mineral demand
Clean energy

ABSTRACT

The transition to low-carbon energy systems will increase demand for a range of critical minerals and metals. As a result, several quantitative demand models have been developed to help understand the projected scale of growth and if, and to what extent, material shortages may become an obstacle to the deployment of clean energy technologies. This research presents one of the first comparative reviews of mineral demand estimates for clean energy technologies and provides a meta-analysis of assumptions, model parameters, and key results. Drawing from academic and gray literature to highlight the variability of mineral demand estimates, we conclude that mineral demand models should be interrogated more critically, and more attention should be paid to recycling industries, creating a more sustainable mining industry, and creating more material-efficient energy technologies.

1. Introduction

The transition to a low-carbon energy system has the potential to deliver transformative benefits to society and the environment. A few renewable energy technologies, including solar photovoltaics (PVs), wind turbines, and lithium-ion batteries, have become central to the energy transition. All of these technologies require "critical minerals" or "critical materials", which are defined as being essential to economic or national security with supply chains vulnerable to disruptions [1,2–5]. As a result, ensuring that the world produces enough materials to build renewable technologies is now a major focus for companies, governments, academics, and other interest groups [1,6–9].

Over the last several decades, researchers have investigated the potential for critical mineral supply shortages and the effects that sudden, unmanageable increases in demand could have on the adoption of renewable technologies [10,11–22]. These investigations often resulted in mineral demand estimates, which are models that estimate how much minerals and metals the world, or specific countries, might need to build renewable technologies under different energy scenarios [23,24,17,25]. The results of these models have shown that demand for critical minerals can grow to exceed known reserves, and that supply shortages can act as "bottlenecks" that delay the adoption of renewable energy technologies [16–18]. Because of this, critical mineral demand models are often used to justify and drive national and international policy, as critical minerals and metals can be considered analogous to oil in that they are intrinsically tied to energy security [10]. Mineral demand models provide insights into the challenges different countries might face with supply chains, or how geopolitics might shift to reflect the growing importance and demand for specific minerals or metals [26]. Many governments look to mineral demand models to inform national strategies and policies related to critical mineral supply chains [6,1,27].

Despite mineral demand estimates underwriting many of the concerns associated with critical mineral shortages, they are not well studied [6,1,27–29]. This research identified over 150 demand models examining material requirements for clean energy technologies but was not able to identify a comparative assessment or breakdown of the models themselves. Liang et al. (2022) comprehensively reviewed the material intensities (e.g., how much steel is needed to build one electric vehicle) used by different models but did not examine the mineral demand estimates themselves [29]. Watari et al. (2020) provided the first systematic review of mineral demand research but included studies that predicted demand from construction and unrelated activities, did not include gray literature such as the International Energy Agency's (IEA) report on critical mineral demand, and compared demand studies that had different objectives or scales (e.g., directly comparing US offshore wind material requirements to global material requirements from all renewable technologies) [28].

* Corresponding author.
E-mail address: jorlee@mines.edu (J.L. Calderon).

https://doi.org/10.1016/j.rser.2023.113938
Received 16 April 2023; Received in revised form 27 September 2023; Accepted 17 October 2023
Available online 31 October 2023
1364-0321/Published by Elsevier Ltd.

Abbreviations:

EV	Electric Vehicle
PV	photovoltaic
Kg	kilogram
GDP	gross domestic product
TWh	tera-watt hour
IEA	International Energy Agency
CdTe	Cadmium Telluride
MW	megawatt
WOS	Web of Science
NGO	Non-governmental Organization
EV	Electric Vehicle
NMC	Nickel–Manganese–Cobalt
NCA	nickel-cobalt-aluminum-oxide
LFP	lithium-iron-phosphate
Kt	kiloton

This research takes a step towards advancing our understanding of future mineral demand by providing a meta-analysis of critical mineral demand models for renewable technologies to compare general trends, underlying assumptions, agreements, disagreements, and the evolution of demand estimates over the last decade. We argue that existing mineral demand estimates are inherently limited and that future modeling and policy efforts should focus on comparative assessments, the effects of recycling industries, an adaptive mining industry, and the material-efficiencies of energy technologies (e.g., how can material requirements be reduced), as they are some of the most important variables affecting mineral demand.

2. How mineral demand models are made

Mineral demand models are largely based on the ability to predict the deployment of clean energy technologies and then calculate the materials needed to build those technologies. As a result, mineral demand models are generally created by considering four primary aspects, as well as a subset of secondary considerations that act as modifiers. These four aspects include: (1) Future Renewable Energy Deployment; (2) Current and Future Renewable Sub-Technologies; (3) Material Intensities of Sub-Technologies; and (4) Dynamic Model Variables.

2.1. Future Renewable Energy Deployment

To calculate the materials required to build future renewable energy technologies, it is necessary to begin with an estimate of how much energy will be needed at some determined time in the future (energy scenario) and how different technologies will work together to supply the energy (energy mix) [23]. Fig. 1 shows how there are several established energy scenarios that predict how much energy will be needed in 2050 and what mix of technologies will likely provide that energy. One such energy scenario is the IEA's Sustainable Development Scenario (IEA SDS), which describes how much renewable energy would be needed to reach the United Nation's energy goals and the goals of the Paris Agreement (Fig. 1) [23]. This scenario is noticeably different that the IEA's Net Zero Emissions (IEA NZE) which shows the energy mix required for the world to achieve net zero CO2 emissions by 2050 (Fig. 1) [23]. Groups like International Renewable Energy Agency (IRENA) have also created scenarios such as the Planned Energy Scenario (IRENA PES), which is based on many governments' current energy plans and other stated policies [30]. Furthermore, oil and gas companies (Shell, Equinor) and other groups have created future energy scenarios and predicted energy mixes based on their own understandings of energy and fossil fuels [31] (Fig. 1). Some mineral demand models base their assumptions about future energy requirements on economic indicators, such as population growth, and chose not to rely on the established scenarios such as those shown in Fig. 1 [18,32,31,33,34]. There are also energy scenarios for battery storage technologies (e.g., lithium-ion batteries), which are related to broader renewable energy demand but are also tied to electric vehicle deployment, such as the IEA's Global EV Outlook, or Bloomberg's Electric Vehicle Outlook [35,36]. Once mineral demand modelers understand future energy requirements, they can begin researching the technologies and materials needed to meet those requirements.

2.2. Current and Future Renewable Sub-technologies

After selecting an energy scenario and energy mix, mineral demand

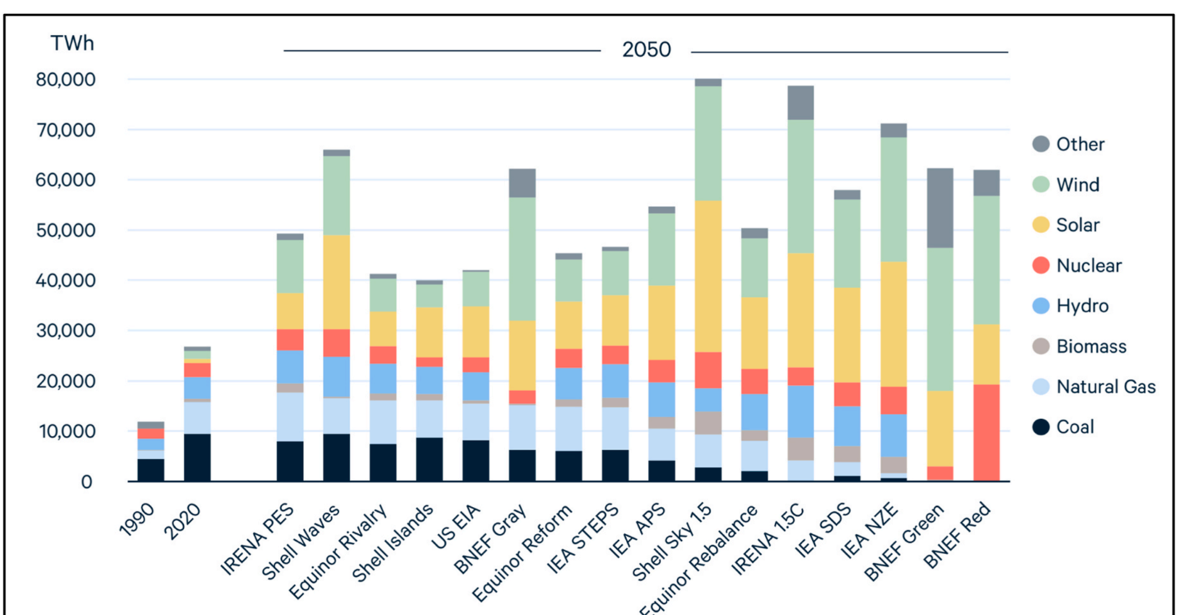

Fig. 1. Global energy demand and energy mix scenarios, Terawatt hours (TWh), (Global Energy Outlook, Resources for the Future, 2022) [37].

modelers must identify which specific sub-technologies will produce the actual energy before calculating material requirements. For example, if an energy scenario and energy mix assume that 20,000 TW h of energy comes from wind in 2050, then the modeler must make assumptions about the future use of offshore wind turbines versus onshore wind turbines since they are both forms of wind energy. The modeler's assumptions about sub-technologies are usually based on what is currently popular, or what the latest research says about emerging technologies. For example, for solar energy, modelers might make the assumption that crystalline silicon solar cells will remain the dominant technology over Cadmium Telluride (CdTe) solar cells, which currently only represent 5 % of the world market [38]. Or due to CdTe solar cells being low-cost, a mineral demand modeler might assume they become the dominant technology in the future. Fig. 2 shows how the IEA predicts that crystalline silicon solar cells will remain the dominant solar technology though 2040 — although there are alternative scenarios where CdTe solar cells comprise a significant market share [23]. Since many of these sub-technologies require different materials, the choices modelers make about the popularity and use of sub-technologies can greatly affect the results of mineral demand models.

2.3. Material Intensities of Sub-technologies

Once sub-technologies have been selected by modelers, it is necessary to research what specific materials are needed to build each sub-technology. This is often referred to as material intensity, and it is how modelers translate energy scenarios into demand estimates for critical minerals and metals. The material requirements for different energy sub-technologies can be described as kilograms of material per megawatt of energy that a technology produces (kg/MW). Fig. 4 shows the tons/MW and kg/MW of different metals required for wind turbines according to Elshkaki and Graedel (2013) and the World Bank (2017). Many energy sub-technologies will have similar material requirements as shown in Fig. 3, but they can also have unique requirements. For example, offshore wind turbines use direct drive generators which use more copper than onshore geared turbines and also require neodymium, and dysprosium [39].

Different data sources can be used to identify material requirements, and they are often based on life cycle assessments or published academic research. Modelers may also do their own independent research to identify the material intensities of different renewable sub-technologies. Where modelers get their data from and what assumptions they make about material requirements can greatly affect mineral demand estimates [10]. For example, Fig. 3 shows how Elshkaki and Graedel (2013) used a combination of academic publications and literature from the Department of Energy and the Nickel Institute to estimate the tons of materials needed to produce 1 MW (MW) of energy from offshore and onshore wind turbines. Conversely, the World Bank (2017) used different sources and came up with different materials requirements to also create 1 MW of energy from wind turbines [41]. According to the World Bank, chromium and molybdenum are also important material considerations, while they are not listed by Elshkaki and Graedel (2013). Conversely, the World Bank listed .8 kgs of boron as a material requirement whole leaving aluminum requirements unknown — which according to Elshkaki and Graedel (2013) is roughly 370 kg/MW. Fig. 3 shows how material intensities can be very different across studies and that wind turbines might require one, two, three, or ten tons of copper depending on what sources are used and what different modelers prioritize.

2.4. Dynamic Model Variables and comparing models

While mineral demand models for renewable technologies can be generally developed using assumptions about energy, technologies, and material requirements, many models also take into consideration dynamic variables — or variables that can change over time. This includes how material requirements can change through recycling, how different technologies can become more efficient (same energy for less materials), the changing policies of industries and governments (China has adopted certain types of batteries), different regional needs (solar installations are cheaper in certain regions), and global economic trends [10,35]. There are ultimately numerous dynamic variables that can be integrated into mineral demand models, since there are numerous variables that are constantly affecting mining, recycling, renewable technologies, and future energy use.

Not all models are created in the same way, and with a wide range of assumptions and dynamic variables constantly being updated, mineral demand models are published with vastly different results. However, this research could not identify any studies that examined how mineral demand models are developing in response to new data or how assumptions about dynamic variables are affecting mineral demand estimates. For example, Fig. 4 shows how IEA energy predictions need to be consistently corrected because they are underestimating how quickly renewable energy technologies will be adopted. It is not clear if any

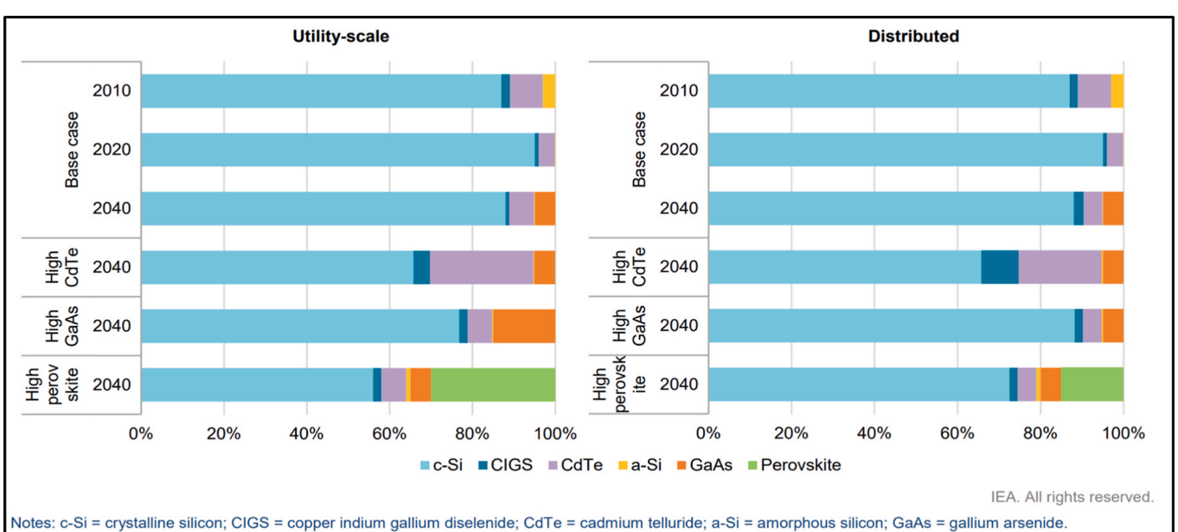

Fig. 2. Share of annual capacity additions by PV technologies under different technology evolution scenarios (The Role of Critical Minerals in Clean Energy Transitions, IEA, 2021) [23].

Metals used in Wind Turbines by Elshkaki and Graedel (2013)

Metals	Onshore (ton/MW)	Offshore (ton/MW)	Source
Steel	132.0	132.0	Garcia-Olivares et.al., 2012
Aluminium	0.37	0.37	Garcia-Olivares et.al., 2012
Copper	2.0	10.0	Garcia-Olivares et.al., 2012
Nickel	0.111	0.111	Nickel Institute
Lead	0	6.72	Schleisner, 2000
Neodymium	0	0.124	US DOE, 2010
Dysprosium	0	0.022	US DOE, 2010

Metals used in Wind Turbines by the World Bank (2017)

Metal	Range of estimates (kilograms/megawatt)	Metal	Range of estimates (kilograms/megawatt)
Aluminum (Al)	Unknown	Molybdenum (Mo)	116–136
Boron (B)	0.8–7.0	Neodymium (Nd)	0–186
Chromium (Cr)	789–902		
Copper (Cu)	1,140–3,000	Nickel (Ni)	557–663
Dysprosium (Dy)	2.8–25.0	Praseodymium (Pr)	4–35
Iron (in magnet)	52–455	Steel	103,000–115,000
		Terbium (Tb)	0.8–7.0
Iron (cast)	20,000–23,900	Zinc (Zn)	5,150–5,750
Lead (Pb)	Unknown		
Manganese (Mn)	32.5–80.5		

Fig. 3. The amount of metals used in wind turbines as proposed by Elshkaki and Graedel (2013) and the World Bank (2017) [40], [41].

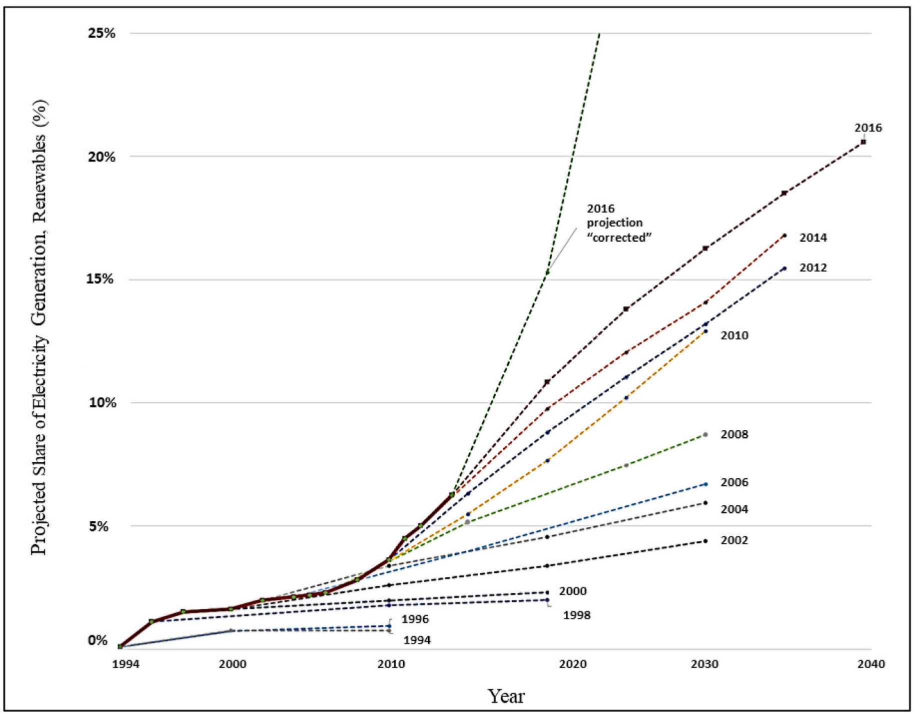

Fig. 4. Projected shares of renewables electricity generation (excluding hydro-electric power) modified from Quiggin (2019) [42].

mineral demand estimates have taken this into account or how they compare with studies that assume global energy predictions are correct. It is also unclear if older studies are inherently less accurate since they rely on older assumptions, or which older studies have proven to be most accurate and why. Ultimately, due to a lack of comparisons, there are many unanswered questions about what exactly mineral demand estimates are describing, how real-world changes can affect future demand, and how the different variables and assumptions used by mineral demand models can be effectively used to navigate the energy transition.

3. Research methods

To compare mineral demand models, this research began with a systematic review of academic literature. Peer-reviewed publications were identified through Web of Science queries using keywords including "energy transition", "low-carbon", "renewable energy", "demand", "material flow analysis", "scenario", "availability", and "outlook". We also used material-related search terms including "critical", "mineral", "metal", "material", "metal demand", "metal constraints", "bottleneck", "metal requirements", "mineral demand", "mineral requirements", as well as renewable energy terms including: "wind", "solar", "electricity", "renewable", "electricity", "electric vehicle", and "batteries". This search resulted in over 2500 identified publications from a wide range of research areas. These articles were then screened with the following selection criteria to ensure comparability between studies: the paper needed to be focused on a renewable energy-driven scenario; the paper looked at material demand on a global scale; and the paper predicted future mineral and metal demand.

This review was expanded on by including relevant gray literature due to the importance of studies by government and non-governmental organizations, such as the International Energy Agency (IEA) (2021) and the World Bank (2020) [23], [24]. These studies were subjected to the same screening criteria as the peer-reviewed publications. If publications with multiple iterations were found, the latest publications were included. This screening resulted in 38 publications that were relevant to this study, as shown in Table 1.

From these 38 publications, data for 25 elements were extracted and consolidated (Fig. 5). Iron, steel, and aluminum were excluded from the dataset due to their broader role in industrial processes, as well as minerals that were examined by less than three studies. All other minerals that were identified in papers were included in the dataset.

Numerous publications were identified during this review that

Table 1
Literature Review Results [23,15–18,32,43–48,39,40,49–71].

Author	Publication Date (month - year)	Publication
McNulty (2022)	Oct-22	Byproduct critical metal supply and demand and implications for the energy transition: A case study of tellurium supply and CdTe PV demand
Sokhna Seck (2022)	Mar-22	Potential bottleneck in the energy transition: The case of cobalt in an accelerating electro-mobility world
Klimenko (2021)	Jul-21	Constraints imposed by key-material resources on renewable energy development
German Mineral Resources Agency (DERA) (2021)	Jul-21	Raw materials for emerging technologies 2021
IEA (2021)	May-21	The Role of Critical Minerals in Clean Energy Transitions
Xu (2020)	Dec-20	Future material demand for automotive lithium-based batteries
Junne (2020)	Nov-20	Critical materials in global low-carbon energy scenarios: The case for neodymium, dysprosium, lithium, and cobalt.
Greim (2020)	Sep-20	Assessment of Lithium Criticality in the Global Energy Transition and Addressing Policy Gaps in Transportation
Zhou (2020)	Aug-20	Dynamic criticality of by-products used in thin-film photovoltaic technologies by 2050
World Bank (2020)	May-20	Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition
TNO (2019)	Nov-19	Global energy transition and metal demand - An introduction and circular economy perspectives
Watari (2019a)	Oct-19	Integrating Circular Economy Strategies with Low-Carbon Scenarios: Lithium Use in Electric Vehicles
Ambrose (2019)	Oct-19	Understanding the Future of Lithium (Part 1) (There is a part 2 that has LCA)
Watari (2019b)	May-19	Total Material Requirement for the Global Energy Transition to 2050: A focus on transport and electricity
Hache (2019)	Apr-19	Critical raw materials and transportation sector electrification: A detailed bottom-up analysis in world transport
Institute for Sustainable Futures (2019)	Jan-19	Responsible Minerals Sourcing for Renewable Energy
Valero (2018b)	Oct-18	Material bottlenecks in the future development of green technologies
Månberger (2018)	Aug-18	Global metal flows in the renewable energy transition: Exploring the effects of substitutes, technological mix and development
Ziemann (2018)	Feb-18	Modeling the potential impact of lithium recycling from EV batteries on lithium demand: A dynamic MFA approach
Weil (2018)	Feb-18	The Issue of Metal Resources in Li-Ion Batteries for Electric Vehicles
de Koning (2018)	Feb-18	Metal supply constraints for a low-carbon economy?
Harvey (2018)	Dec-17	Resource implications of alternative strategies for achieving zero greenhouse gas emissions from light-duty vehicles by 2060
Zhou (2017)	Oct-17	Global Potential of Rare Earth Resources and Rare Earth Demand from Clean Technologies
Davidsson (2017)	Sep-17	Material requirements and availability for multi-terawatt deployment of photovoltaics
Sverdrup (2016)	Nov-16	Modeling global extraction, supply, price and depletion of the extractable geological resources with the LITHIUM model
Hun Choi (2016)	Nov-16	System Dynamics Modeling of Indium Material Flows under Wide Deployment of Clean Energy Technologies
McLellan (2016)	May-16	Critical Minerals and Energy–Impacts and Limitations of Moving to Unconventional Resources
Elshkaki (2015)	Aug-15	Solar cell metals and their hosts: A tale of oversupply and undersupply
Albach/Pehlken (2015)	Jul-15	Is there a resource constraint related to lithium ion batteries in cars?
Stamp (2014)	Dec-14	Linking energy scenarios with metal demand modeling–The case of indium in CIGS solar cells
Habib (2014)	Dec-14	Exploring rare earths supply constraints for the emerging clean energy
Bustamante (2014)	Jun-14	Challenges in assessment of clean energy supply-chains based on byproduct minerals: A case study of tellurium use in thin film photovoltaics
World Wide Fund for Nature (2014)	Jan-14	Critical materials for the transition to a 100 % sustainable energy future contents
Elshkaki (2013)	Nov-13	Dynamic analysis of the global metals flows and stocks in electricity generation technologies
Hoenderdaal (2013)	Jan-13	Can a dysprosium shortage threaten green energy technologies?
Mohr (2012)	Mar-12	Lithium Resources and Production: Critical Assessment and Global Projections
Kushnir (2012)	Jan-12	The time dimension and lithium resource constraints for electric vehicles
Zuser (2011)	Oct-11	Considerations of resource availability in technology development strategies: The case study of photovoltaics

examined growing demand for minerals and metals from global industrialization and other non-energy-related activities. While these studies were used as references, many were not implicitly comparable to studies that focused solely on mineral demand from renewable technologies and were thus excluded from this analysis. Publications were also excluded that predicted mineral demand for renewable technologies for specific regions or nations, as they often differed in order of magnitude and could not be compared to global estimates. Notably, this included numerous publications on China's future demand and reports prepared by the European Commission that were specific to European countries [72–82].

Publications were included that focused on future mineral demand and which predicted demand for more than ten years from their publication date to ensure comparability and accuracy. Studies that did not predict future demand were not included. Qualitative discussions of future mineral demand or publications where mineral demand did not serve as a primary focus were not included [10,83].

The data that was extracted from publications focused on the mineral and metal demands of renewable technologies. In many publications, the exact data for mineral demand estimates were not always provided in the publications, and therefore, many data points used in this analysis

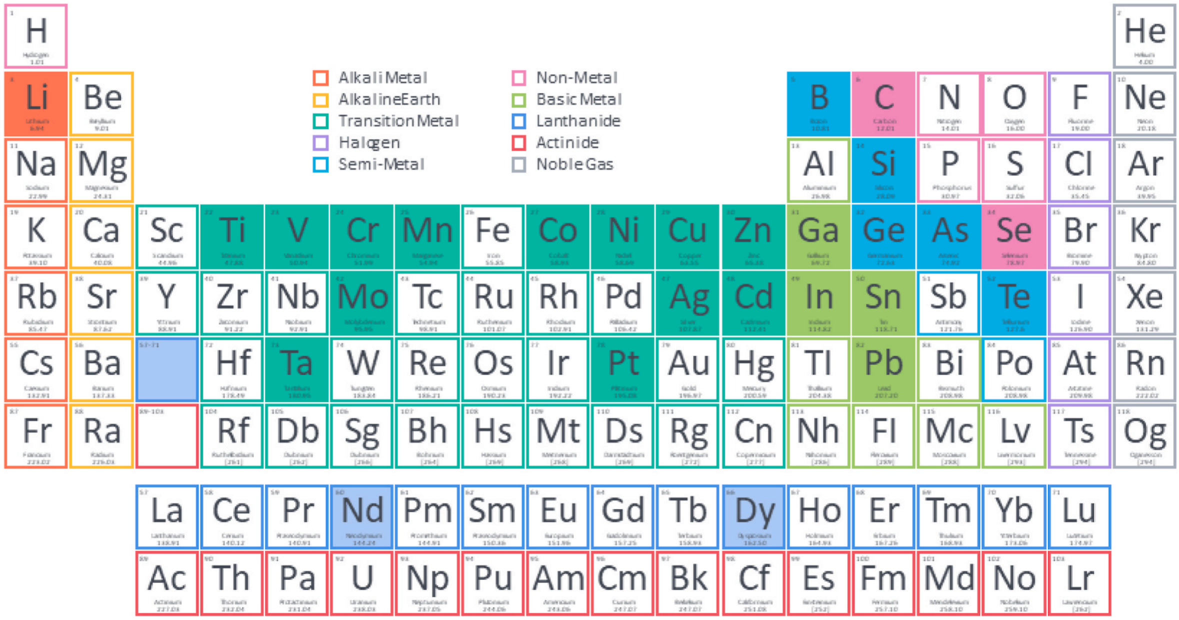

Fig. 5. Elements included in this review are highlighted (carbon refers to graphite).

were extracted or extrapolated from figures and plotted values. Studies with inaccessible or unverifiable estimates were not included. Fossil-fuel focused energy scenarios were also not included as they were not based on renewable energy deployment. To enable greater comparability, demand estimates were converted to kilotons/year and plotted from 2020 to 2050. The starting year of 2020 was used for all data sets, even if a study was published before 2020. The 2020 data points for all minerals were based on real-world demand for critical minerals from renewable technologies as taken from the IEA's study on critical minerals — i.e., all studies were assumed to have correctly predicted 2020 demand to help enable comparability and to focus on differences in future material demand projections [23]. Possible errors may have occurred during the extraction of data from charts or from the extrapolation of the data. These errors should have a limited effect on the results, as this research discusses broader trends, and collected values should not be considered a substitute for the data presented in the original publications.

If a study only considered one technology and that technology uses the same materials as other prominent renewables, some of those values were excluded. For example, Xu et al. (2020) examined electric vehicles (EVs) and provided data on copper demand from EVs through 2050 [84]. However, because copper plays an important role in all renewable technologies and Xu et al. (2020) only looked at EVs, this research excluded the copper values. The demand for copper from an EV study cannot be accurately compared to a study that looked at global demand for copper from *all* renewable technologies including EVs, solar energy, wind energy, and electricity networks. However, Xu et al.'s lithium values were included in the dataset because lithium is not commonly used in other renewable technologies besides energy storage, and electric vehicles already account for 80 % of all lithium demand [35,36]. The relative importance of different materials for different technologies can be seen in Fig. 6.

4. Results and discussion

There is a general agreement that mineral and metals requirements for the energy transition will increase substantially between 2020 and 2050 — but almost all studies disagree on the scale, timeline, and rate of demand increase. For example, some studies estimate that future demand will outpace known reserves within the next few years, while others predict that material shortages will be offset by recycling and that

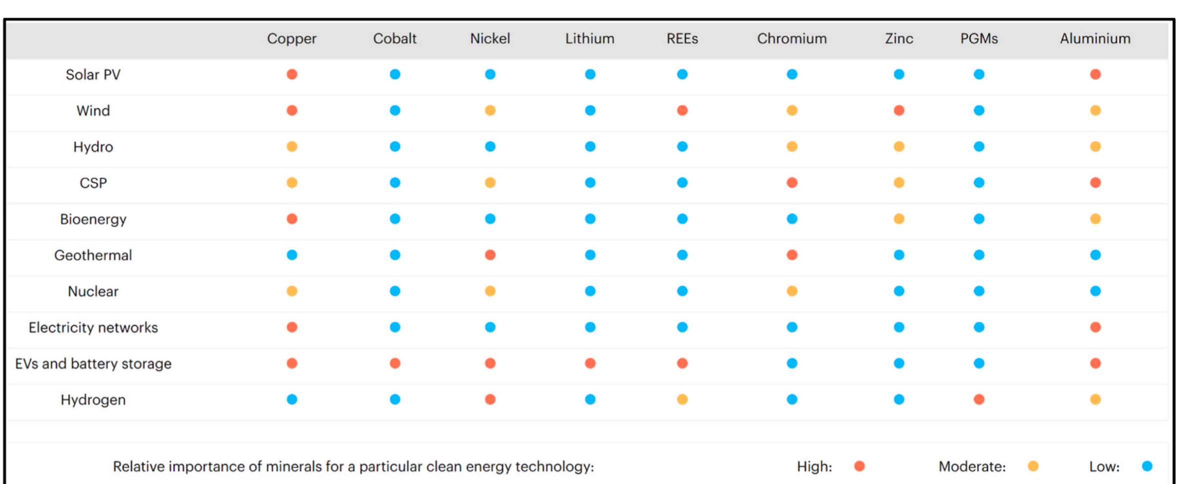

Fig. 6. Critical mineral needs for clean energy technologies, Iea (2021) [23].

demand can be effectively managed without supply disruptions. Fig. 7 shows the annual demand (kilotons per year) predicted by different studies through 2050 for commonly discussed critical minerals.

Almost all studies show large increases in demand for critical minerals to the point that real-world 2020 production (the starting point for all charts in Fig. 7) often appears to be negligible and nonexistent in the graphical representations. Many models also predict that demand will not continuously increase through 2050, and that at some point demand will peak before declining due to recycling or other changes in mineral markets (e.g., Tellurium in Fig. 7).

Studies referenced in this analysis had similar approaches to estimating demand for different minerals (e.g., calculating material demand from energy requirements as outlined in Section 2), but no two studies were the same. In many studies, the term 'demand' was often used interchangeably with 'annual material requirements', but many sources also differentiated between gross demand, cumulative demand, annual demand, demand for virgin metal, primary production, secondary production, open-loop recycling, and closed-loop recycling [22]. Some studies combined these considerations to develop 'high" and 'low" demand scenarios, while other studies kept recycling and other considerations separate from their demand estimates. With many studies having unique considerations and language, the results of this analysis focus on the major components of the models (predicted demand, energy scenarios, materials, recycling), how they differ, and how these differences affect accuracy and use of models.

4.1. Disagreement in mineral demand estimates

The ranges of annual demand for critical minerals and metals show that demand estimates disagree on orders of magnitude — meaning that one study predicts that demand will increase to ten times current demand, while another predicts an increase of 100 times current demand for the same mineral. Fig. 8 shows the possible demand ranges for many critical minerals in 2050 using box and whisker plots to help highlight the outliers (circles), lower quartile values, median values, and upper quartile values.

Future lithium demand was the most explored scenario (24 studies). Annual demand for lithium in the year 2050 was estimated to range from 146,000 to 6,800,000 tons (Fig. 8), with a standard deviation of ~1,400,000 tons. The average predicted demand when including outliers was roughly 1,100,000 tons of lithium per year in 2050. Global lithium mine production was 130,000 tons in 2022 (for all end-uses, not just renewables), and global reserves were estimated to total 26, 000, 000 tons by the U.S. Geological Survey in 2023 [85]. This means that future annual demand for lithium could require more than 25 % of all currently identified reserves, and on average the studies predicted that lithium demand will be almost 12 times higher than current annual production.

Similarly, cobalt demand was the second most explored scenario and annual demand for cobalt in 2050 is estimated to range between 6000 tons and 3,600,000 tons, with a standard deviation of 880,000 tons. Global cobalt mine production was 190,000 tons in 2022 (for all end-uses, not just renewables), and global reserves were estimated to total 8,300,000 tons by the U.S. Geological Survey in 2023 [25]. This means that annual cobalt demand in 2050 could equal anywhere from 1.2 to 43 % of current global reserves respectively.

Identified demand ranges for many critical minerals are large enough for some studies to argue that material shortages and supply crunches are imminent, especially in the context of published reserve estimates and how quickly demand is expected to increase. However, economists and geologists have consistently maintained that price increases for materials will continue to modify reserve estimates and that "running out" of minerals is extremely unlikely [19,86]. Similarly, studies with lower demand estimates speculate that demand will only increase slightly or that recycling will limit new demand, and the transition to renewables will not cause significant changes in industrial practices. These disagreements about demand ranges means there are contradictory conclusions among the studies on the relative importance of critical minerals in enabling energy transitions.

Even among studies that used the exact same energy scenarios, differences in demand estimates were substantial and often led to different conclusions. For example, four studies examined lithium in the context of transportation and EVs, and all four used the same energy scenario (IEA 2017 Beyond 2 Degrees Scenario) as the basis of their analysis [87]. Despite using the same energy assumptions, their lithium demand estimates differed greatly, as shown in Table 2.

Large differences in mineral demand estimates make it challenging to speculate on whether mineral markets are advancing fast enough or whether market signals will remain strong enough to minimize demand shocks. Depending on which study is consulted, global production volumes for many minerals are either already aligned with renewable energy deployment scenarios, or production needs to increase rapidly in the next few years.

4.2. Variation in the scope of technologies considered

The specific technologies that are considered in mineral demand estimates can greatly impact the results of the estimates and can support or discredit the assumptions that certain minerals and metals will face supply challenges. When mineral demand estimates assume that a certain percentage of future energy will be provided by a type of renewable energy (solar, wind, electric vehicles), they must also make assumptions about sub-technologies, market shares, and associated infrastructure. These assumptions were inconsistent throughout the mineral demand estimates and even led to differing conclusions on what minerals should be of particular concern for the energy transition.

For example, due to differences in assumptions about infrastructure, copper demand for renewables appears to decrease in some of the models shown in Fig. 9. The 2020 starting value for all models shown in Fig. 9 is the actual, real-world 2020 demand for copper from renewable technologies as reported by the IEA (5715 kilotons) [23]. 87 % of the copper demand for renewables in 2020 came from electricity networks (4975 kilotons), including transmission, distribution, and transformers [23]. However, because studies such as those conducted by the World Bank (2020) frequently choose not to include any type of infrastructure in their analysis, they also effectively ignore 87 % of the copper demand that renewables might create from 2020 to 2050 [54]. As a result, their demand model predicts that future demand will actually decrease from current levels, as 4975 kilotons is already higher than their future estimates [54]. When ignoring infrastructure, the World Bank estimates that only 7 % of future annual copper production will be used for renewable technologies, while the IEA predicts that renewables will grow to account for 40 % of all copper demand within the next few decades primarily due to infrastructure [23,54]. In fact, out of all the demand estimates, the IEA predicted the highest copper demand because it covered numerous technologies and was one of the only studies to consider transmission, distribution, and transformers in its analysis.

Aside from what studies can choose to include or exclude, assumptions about the future popularity of specific renewable technologies were also inconsistent and found to greatly affect the results of mineral demand estimates. In particular, the decisions about the future market shares of battery technologies and photovoltaic technologies differed greatly across studies and determined whether demand for specific minerals would increase substantially or negligibly. For example, most demand models predicted that cadmium and tellurium demand would not increase at the same scale or rate as lithium and other critical minerals. After all, cadmium telluride (CdTe) solar cells currently only account for 5 % of the world market, while crystalline silicon photovoltaic cells have maintained 85–95 % of market sales since 2011 [38, 88,89]. However, as shown in Fig. 10, in scenarios where CdTe solar cells become more popular, annual demand for cadmium and tellurium can increase by 11,000 to 13,000 %.

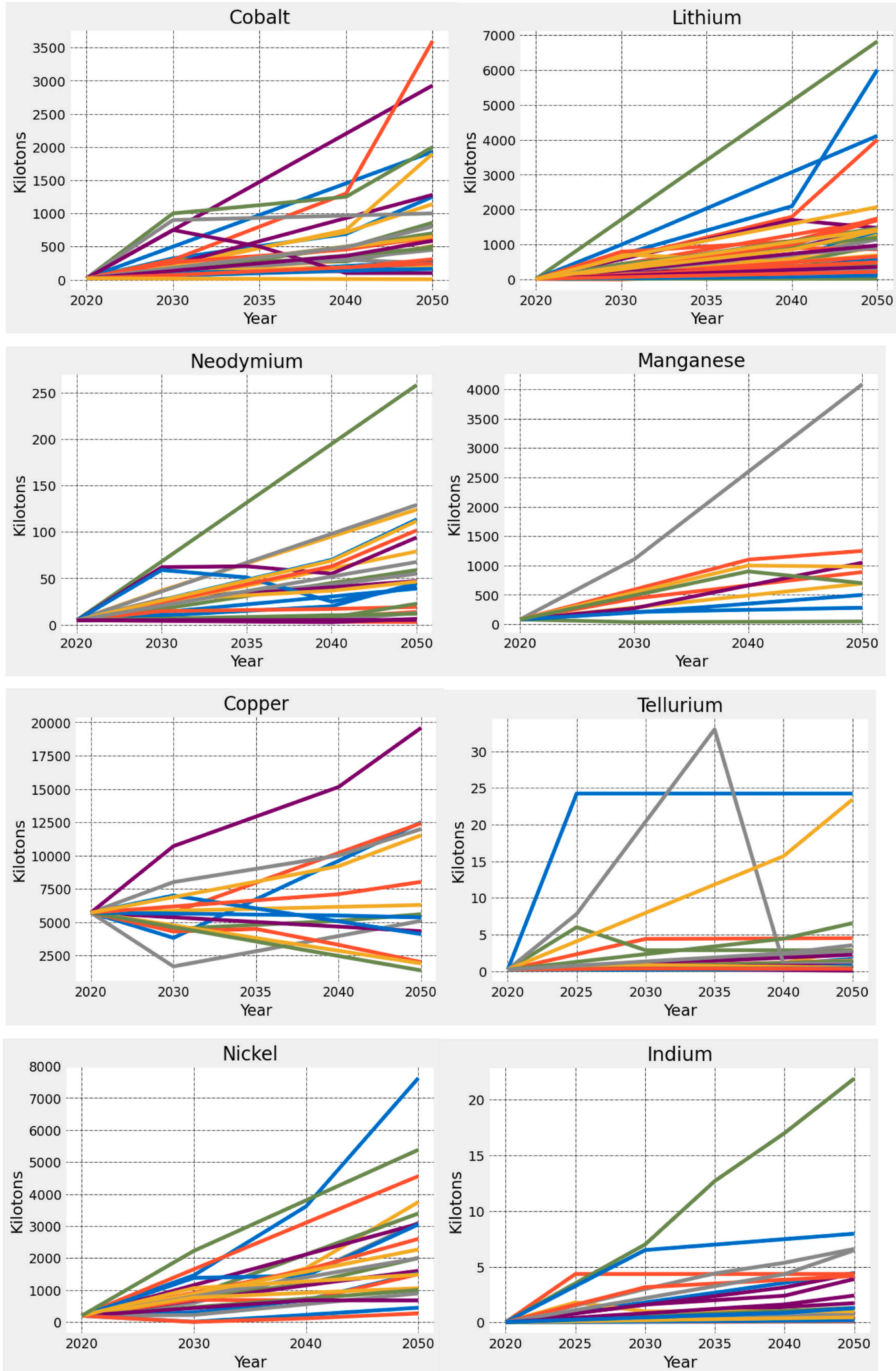

Fig. 7. Annual demand for critical minerals from 2020 to 2050 (kt).

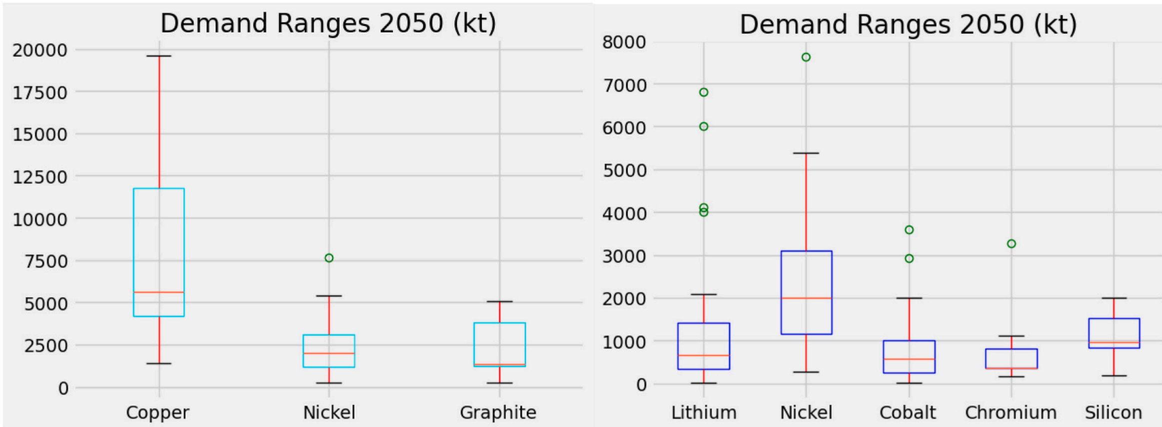

Fig. 8. Box and whisker plots for select minerals and metals.

Table 2
Lithium demand estimates from studies using the same energy scenario.

Author	Geographic Scope	Mineral	year	kt/year	Percent of 2020 Lithium Demand	Climate Scenario
World Bank (2020)	World	Lithium	2050	415	1923.64 %	**IEA Beyond 2 Degrees (2017)**
Watari (2019b)	World	Lithium	2050	660	3059.28 %	**IEA Beyond 2 Degrees (2017)**
Månberger (2018)	World	Lithium	2050	1470	6813.86 %	**IEA Beyond 2 Degrees (2017)**
Junne (2020)	World	Lithium	2050	2630	12190.78 %	**IEA Beyond 2 Degrees (2017)**

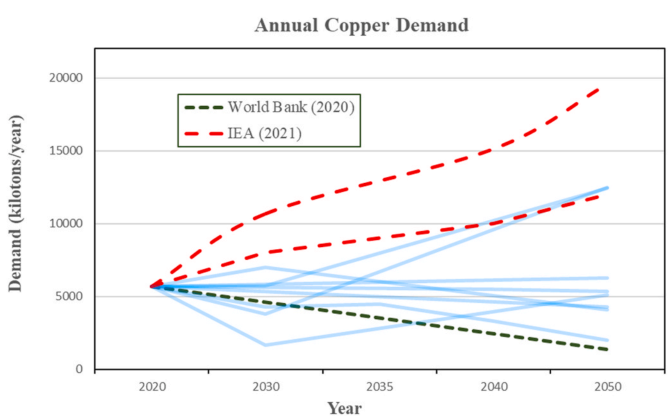

Fig. 9. Annual copper demand through 2050.

For battery materials, demand estimates for specific minerals were largely dependent on what type of battery the models assumed would be prevalent, how quickly battery types could be adapted for industrial processes, and how quickly new types of batteries could be commercialized (e.g., lithium-air). Lithium-ion batteries with nickel-manganese-cobalt (NMC) cathodes typically require almost eight times more cobalt than nickel-cobalt-aluminum-oxide (NCA) lithium batteries, but also usually require much less nickel [23,84]. Other types of batteries include lithium-iron-phosphate (LFP) batteries, which do not require nickel, cobalt, or manganese, but instead require 50 % more copper than NMC batteries [23,84]. As a result of the different material requirements, the assumptions that models made about NMC, NCA, and LFP battery technologies had noticeable effects on demand for the materials that are in one battery type, but not others.

Disagreements on sub-technologies and market shares result in dramatically different estimates for mineral demand. While mineral demand models are meant to be speculative, and many models use multiple scenarios in their analysis, there appears to be a great deal of uncertainty around what materials and technologies to prioritize, especially for battery and solar materials.

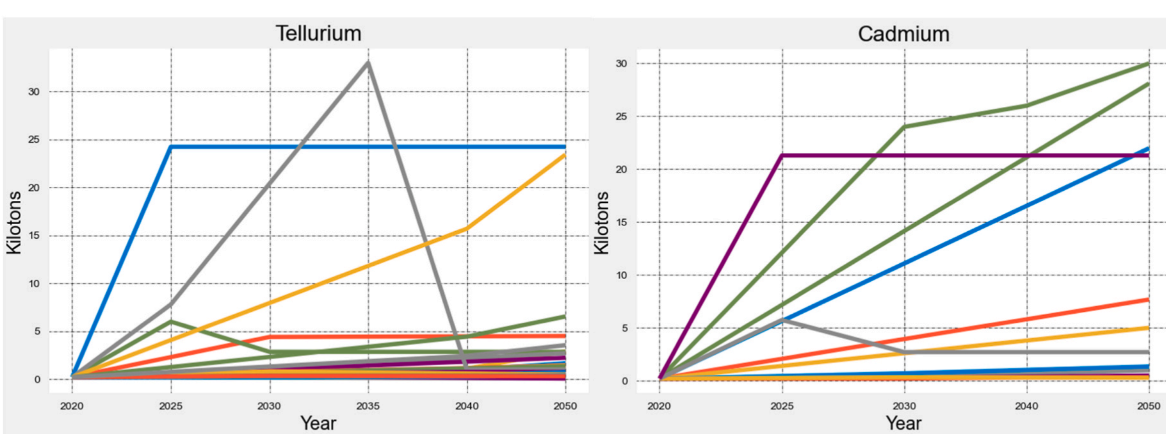

Fig. 10. Annual demand for Tellurium and Cadmium through 2050.

4.3. Assumptions about material intensity and recycling

Assumptions about material intensities (the quantity of minerals or metals needed to build a low-carbon technology) and recycling also often resulted in drastic changes to projected mineral demand estimates and remained inconsistent across most studies. Of the 38 studies included in this analysis, 32 (84 %) modeled the effects of recycling in some form. However, only 10 (26 %) articles considered changes in material intensity due to technological improvement. Furthermore, no two studies were found to make the same assumptions about recycling or material intensities despite their importance to modeling future mineral demand.

The inclusion of recycling in most models emphasizes its importance for mineral demand estimates, but there did not appear to be any consistent way of estimating future recycling rates. Many studies either relied on external estimations of future recycling, such as the United Nations' *Recycling rates of metals: A status report on recycling trends*, or assumed an annual recycling growth rate as shown in Fig. 11 [90]. Some studies differentiated between open-loop and closed-loop recycling, and others integrated renewable life cycles to help estimate when materials would become available, but overall rates, timelines, and considerations were usually unique to each study. This implies that there is no consensus or consistent way of estimating how future recycling can affect future demand.

Assumptions about the minerals required to build different renewable technologies (material intensities) were also inconsistent across studies. The analysis presented here aligns with the first comprehensive review of material intensities conducted by Liang et al. (2022) who showed that mineral demand studies used a wide variety of assumptions about what materials are required to build different renewable technologies (Fig. 12) [29]. For battery electric vehicles, Liang et al. (2022) found that studies estimated anywhere from 600 to 15,000 g of lithium per vehicle, which draws parallels to annual lithium demand estimates ranging from 146,000 to 6,800,000 tons [29]. Similarly, the amount of cobalt needed in an EV was anywhere from 700 to 7000 g depending on which is used, and annual cobalt demand ranges from 6000 tons to 3, 600,000 tons [29]. Fig. 12 shows the ranges of different studies used when calculating the amount of minerals required to build an electric vehicle.

Beyond general disagreement on material intensities when modeling, many studies overlooked the importance of how material intensities might change through 2050. The real price of lithium-ion cells, scaled by their energy capacity, has declined roughly 97 % since their introduction in 1991, and about 38 % of the observed cost decline is from increases in cell charge density [91,92]. This trend has continued for many clean energy technologies, with photovoltaic module (solar) and wind turbine costs also declining until 2021 when the prices of key minerals spiked [93,94]. Despite this, of the 38 studies used in this analysis, only 10 (26 %) articles considered changes in material intensity due to technological improvement. Liang et al. (2022) similarly found that only 13 out of 132 (10 %) papers took a dynamic approach and considered changes in material intensity due to technological improvements [29].

5. Conclusions

This study found that mineral demand estimates, while valuable for understanding general trends and concerns, are inconsistent in their approaches and have a wide range of results that would benefit from comparisons and real-world context. In particular, the ambiguity of future energy technologies (market share, material requirements, etc.) and the difficulties of predicting technological advancements, demonstrates the need to move conversations away from relying on independent predictive models, and toward comparative frameworks and real-world considerations. Many of the current critical mineral models summarize the implications of mineral demand estimates in terms of shortages and supply disruptions, and while these are important, it is equally important to understand what changes can be made, what

	Current recycling rate	Annual growth	2050 recycling rate
Ag	30%	0.6%	37%
Cd	25%	1.3%	39%
Co	32%	1.8%	59%
Cr	20%	2.5%	47%
Dy	10%	0.9%	13.7%
In	37.5%	0.5%	44.7%
Li	1%	4.6%	4.8%
Mn	37%	0.1%	38%
Mo	33%	0.7%	42%
Nd	5%	0.1%	5.2%
Ni	29%	1%	41%
Se	5%	2%	10%
Sn	22%	0.1%	22.8%
Ta	17.5%	0.1%	18.2%

Fig. 11. Recycling rates used in mineral demand estimates by Valero (2018) [17].

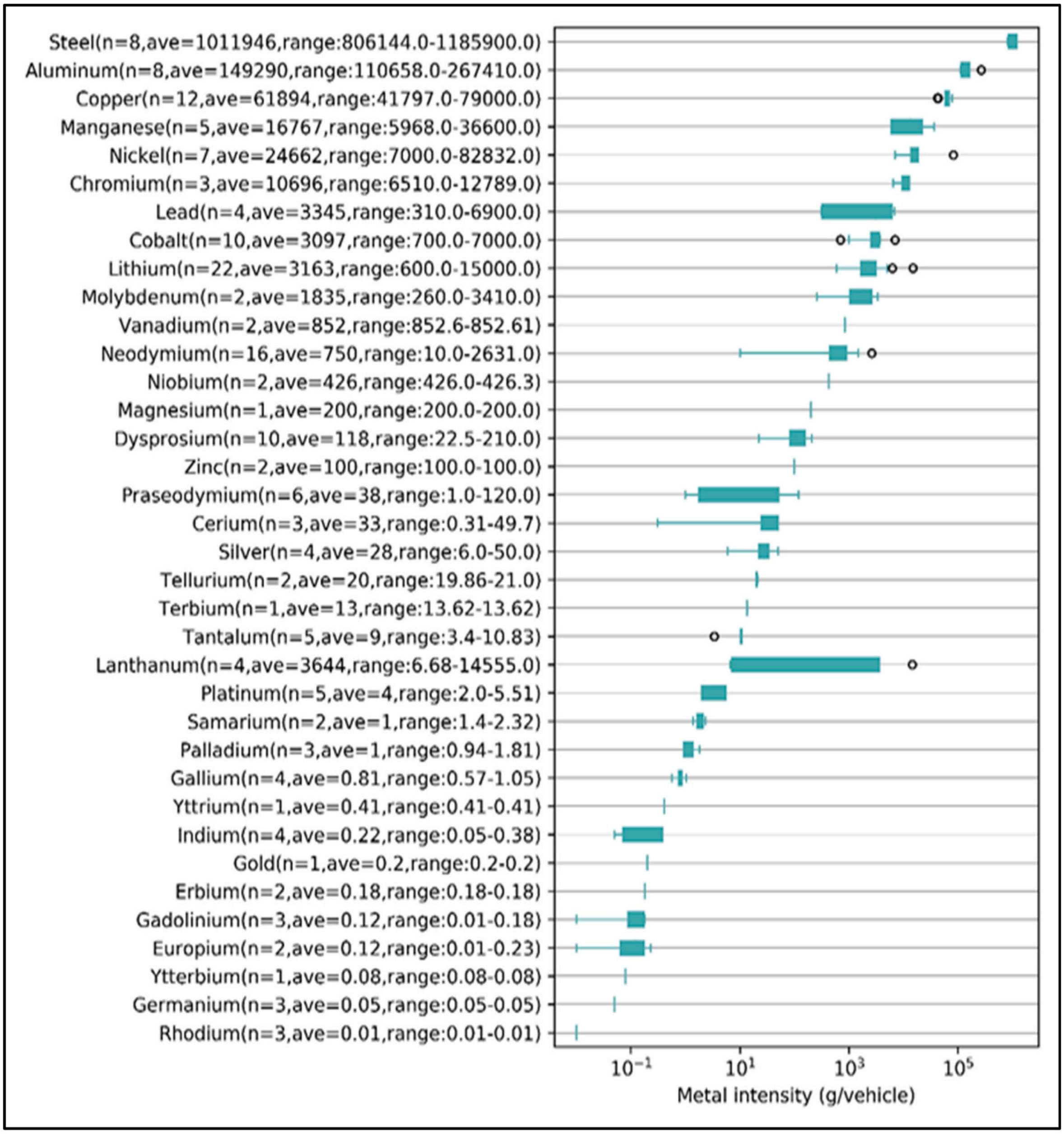

Fig. 12. The amount of metals need to build an electric vehicle according to different studies (g/vehicle, 'n' represents the number of the data dots) (Liang et al., 2022), [29].

options and pathways exist, and how models can be utilized to identify barriers beyond raw material requirements. To this end, it is equally important to understand demand aspects, innovation, and efficiency, as they appear to be broadly underlying and influencing almost every model through their impacts on energy, technologies, and material intensities.

The effects of recycling, the development of more mineral-efficient technologies, and the ability to actually mine and/or process *any* of the predicted demand scenarios are much more important for future material requirements than almost any other consideration. The ability to meet demand estimates is largely dependent on the ability to develop new mines, which is rarely discussed or applied to this class of models. The inclusion of recycling is important to minimize future demand, but it is unclear how recycling will be developed, or what role the current mining and metals industry will play if any at all. These considerations need to be better explored if future demand is to be effectively managed, and mineral demand models play an important role in identifying future pathways.

Ultimately, predictive models have served their role in raising awareness for material concerns, but it is time to advance the conversation toward facilitating the availability of critical minerals. This renewed focus should revolve around strengthening the mining and metals industry so that it can effectively navigate demand shocks, understanding and integrating technological advancements beyond a speculative nature, developing plans for how recycling or circular economies could meet demand, and understanding real world barriers to responsible production through environmental, social, or governance considerations.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Jordan Lee Calderon reports financial support was provided by

National Science Foundation.

Data availability

Data will be made available on request.

Acknowledgments

The work was funded by NSF Growing Convergence Research award #2120721 as part of the project “Responsible Critical Elements.”

We are grateful for the generous support of the Alfred P. Sloan Foundation, and the ongoing partnership with KAPSARC.

References

[1] Service Canada. Canada’s critical minerals strategy. https://www.canada.ca/en/campaign/critical-minerals-in-canada/canada-critical-minerals-strategy-discussion-paper.html. Oct. 24, 2022.
[2] “Critical minerals and U.S. Public policy,” congressional research service, R45810. Jun. 2019. Mar. 20, 2021. [Online]. Available: https://crsreports.congress.gov/product/details?prodcode=R45810.
[3] Department Interior. Final list of critical minerals 2018. Fed Regist May 18, 2018; 83:23295–6 [Online]. Available: https://www.federalregister.gov/d/2018-10667.
[4] Department of Industry. Science, and Resources, “Critical Minerals Strategy 2022 2022. Sep. 27, https://www.industry.gov.au/publications/critical-minerals-strategy-2022. Oct. 24, 2022.
[5] European Commission. Study on the review of the list of critical raw materials : final report. European Commission; Sep. 2017 [Online]. Available: https://publications.europa.eu/en/publication-detail/-/publication/08fdab5f-9766-11e7-b92d-01aa75ed71a1/language-en. [Accessed 2 July 2019].
[6] White House The. The Presidential executive order on a federal strategy to ensure secure and reliable supplies of critical minerals | the white house. The White House; 2020. https://www.whitehouse.gov/presidential-actions/presidential-executive-order-federal-strategy-ensure-secure-reliable-supplies-critical-minerals/.
[7] Press corner, European Commission - European Commission. https://ec.europa.eu/commission/presscorner/detail/en/STATEMENT_22_5523. Jan. 06, 2023.
[8] Department of Industry. Science, and Resources, “Investing in Australia’s critical minerals. 2022. Sep. 12, https://www.industry.gov.au/mining-oil-and-gas/minerals/critical-minerals/investing-critical-minerals-australia. [Accessed 6 January 2023].
[9] Farchy J, Warren H. China’s cobalt is a secret weapon in the race to dominate electric cars,” Bloomberg.com. 2018. Dec. 02, https://www.bloomberg.com/graphics/2018-china-cobalt/. [Accessed 2 June 2019].
[10] Lee J, et al. Reviewing the material and metal security of low-carbon energy transitions, vol. 124. Renewable Sustainable Energy Rev.; May 2020, 109789.
[11] Gruber PW, Medina PA, Keoleian GA, Kesler SE, Everson MP, Wallington TJ. Global lithium availability: a constraint for electric vehicles? J Ind Ecol Oct. 2011; 15(5):760–75.
[12] Olivetti EA, Ceder G, Gaustad GG, Fu X. Lithium-ion battery supply chain considerations: analysis of potential bottlenecks in critical metals. Joule Oct. 2017; 1(2):229–43.
[13] Yaksic A, Tilton JE. Using the cumulative availability curve to assess the threat of mineral depletion: the case of lithium. Resour Pol Dec. 2009;34(4):185–94.
[14] Kleijn R, van der Voet E. Resource constraints in a hydrogen economy based on renewable energy sources: an exploration. Renewable Sustainable Energy Rev Dec. 2010;14(9):2784–95.
[15] Habib K, Wenzel H. Exploring rare earths supply constraints for the emerging clean energy technologies and the role of recycling. J Clean Prod Dec. 2014;84:348–59.
[16] Junne T, Wulff N, Breyer C, Naegler T. Critical materials in global low-carbon energy scenarios: the case for neodymium, dysprosium, lithium, and cobalt. Energy Nov. 2020;211:118532.
[17] Valero A, Valero A, Calvo G, Ortego A. Material bottlenecks in the future development of green technologies, vol. 93. Renewable Sustainable Energy Rev.; Oct. 2018. p. 178–200.
[18] Seck GS, Hache E, Barnet C. Potential bottleneck in the energy transition: the case of cobalt in an accelerating electro-mobility world. Resour Pol Mar. 2022;75: 102516.
[19] Mudd GM, Jowitt SM. Global resource assessments of primary metals: an optimistic reality check. Nat Resour Res Apr. 2018;27(2):229–40.
[20] Moss RL, Tzimas1 E, Kara H, Willis P, Kooroshy J. Critical metals in strategic energy technologies : assessing rare metals as supply-chain bottlenecks in low-carbon energy technologies. JRC – Institute for Energy and Transport 2Oakdene Hollins Ltd 3 The Hague Centre for Strategic Studies; Sep. 2014. https://doi.org/10.2790/35600.
[21] Grandell L, Lehtilä A, Kivinen M, Koljonen T, Kihlman S, Lauri LS. Role of critical metals in the future markets of clean energy technologies. Renew Energy Sep. 2016;95:53–62.
[22] Nguyen RT, Eggert RG, Severson MH, Anderson CG. Global electrification of vehicles and intertwined material supply chains of cobalt, copper and nickel. Resour Conserv Recycl Apr. 2021;167:105198.
[23] The International Energy Agency. The role of critical minerals in clean energy transitions. IEA; May 2021 [Online]. Available: https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions. [Accessed 13 August 2022].
[24] k. h. d. La Porta Thao P. Fabregas Tim Laing John Drexhage, “Climate-Smart Mining: Minerals for Climate Action,” World Bank. Accessed: Jun. 25, 2019. [Online]. Available: https://www.worldbank.org/en/topic/extractiveindustries/brief/climate-smart-mining-minerals-for-climate-action.
[25] U.S. Department of Energy, “U.S. Department of energy - critical materials strategy. December: U.S. Department of Energy; 2011 [Online]. Available: https://www.energy.gov/sites/prod/files/2016/12/f34/2010%20Critical%20Materials%20Strategy%20Report.pdf.
[26] Lee J, Bazilian M, Sovacool B. Reviewing the material and metal security of low-carbon transitions. Renewable Sustainable Energy Rev.; 2020.
[27] McNulty BA, Jowitt SM. Barriers to and uncertainties in understanding and quantifying global critical mineral and element supply. iScience Jul. 2021;24(7): 102809.
[28] Watari T, Nansai K, Nakajima K. Review of critical metal dynamics to 2050 for 48 elements. Resour Conserv Recycl Apr. 2020;155:104669.
[29] Liang Y, Kleijn R, Tukker A, van der Voet E. Material requirements for low-carbon energy technologies: a quantitative review, vol. 161. Renewable Sustainable Energy Rev.; Jun. 2022, 112334.
[30] Global Renewables Outlook. Energy transformation 2050. International Renewable Energy Agency; 2020.
[31] Apergis N, Payne JE. Renewable energy consumption and economic growth: evidence from a panel of OECD countries. Energy Pol Jan. 2010;38(1):656–60.
[32] Mohr SH, Mudd GM, Giurco D. Lithium resources and production: critical assessment and global projections. Minerals Mar. 2012;2(1):65–84.
[33] Schipper BW, Lin H-C, Meloni MA, Wansleeben K, Heijungs R, van der Voet E. Estimating global copper demand until 2100 with regression and stock dynamics. Resour Conserv Recycl May 2018;132:28–36.
[34] Deetman S, Pauliuk S, van Vuuren DP, van der Voet E, Tukker A. Scenarios for demand growth of metals in electricity generation technologies, cars, and electronic appliances. Environ Sci Technol Apr. 2018;52(8):4950–9.
[35] “Global EV Outlook 2023,” IEA. https://www.iea.org/reports/global-ev-outlook-2023 (accessed August. 5, 2023).
[36] EVO report 2023,” BloombergNEF, jun. 08. 2023. https://about.bnef.com/electric-vehicle-outlook/. Sep. 25, 2023.
[37] Global Energy Outlook,” Resources for the Future. https://www.rff.org/publications/data-tools/global-energy-outlook/(accessed October 25, 2022).
[38] Cadmium Telluride,” Energy.gov. https://www.energy.gov/eere/solar/cadmium-telluride (accessed Feb. 05, 2023).
[39] World Wide Fund for Nature. Critical materials for the transition to a 100% sustainable energy future. ECOGYS. [Online]. Available: https://awsassets.panda.org/downloads/critical_materials_report__jan_2014_lr.pdf.
[40] Elshkaki A, Graedel TE. Dynamic analysis of the global metals flows and stocks in electricity generation technologies. J Clean Prod Nov. 2013;59:260–73.
[41] World Bank. The growing role of minerals and metals for a low carbon future. The World Bank; Jun. 2017, 117581. Jul. 02, 2019. [Online]. Available: http://www-wds.worldbank.org/external/default/WDSContentServer/WDSP//.
[42] Quiggin J. “Please, no more projections. What we need are predictions, and they’re harder,” the Conversation, Nov. 18. Sep. 25, 2023. [Online]. Available: http://theconversation.com/please-no-more-projections-what-we-need-are-predictions-and-theyre-harder-126734; 2019.
[43] Davidsson S, Höök M. Material requirements and availability for multi-terawatt deployment of photovoltaics. Energy Pol Sep. 2017;108:574–82.
[44] Stamp A, Wäger PA, Hellweg S. Linking energy scenarios with metal demand modeling–The case of indium in CIGS solar cells. Resour Conserv Recycl Dec. 2014; 93:156–67.
[45] Bustamante ML, Gaustad G. Challenges in assessment of clean energy supply-chains based on byproduct minerals: a case study of tellurium use in thin film photovoltaics. Appl Energy Jun. 2014;123:397–414.
[46] Pehlken A, Albach S, Vogt T. Is there a resource constraint related to lithium ion batteries in cars? Int J Life Cycle Assess Jan. 2017;22(1):40–53.
[47] Kushnir D, Sandén BA. The time dimension and lithium resource constraints for electric vehicles. Resour Pol Mar. 2012;37(1):93–103.
[48] Sverdrup HU. Modelling global extraction, supply, price and depletion of the extractable geological resources with the LITHIUM model. Resour Conserv Recycl Nov. 2016;114:112–29.
[49] McNulty BA, Jowitt SM. Byproduct critical metal supply and demand and implications for the energy transition: a case study of tellurium supply and CdTe PV demand, vol. 168. Renewable Sustainable Energy Rev.; Oct. 2022, 112838.
[50] German Mineral Resources Agency (DERA). Raw materials for emerging technologies 2021. DERA; Aug. 2021 [Online]. Available: https://www.bgr.bund.de/DE/Gemeinsames/Produkte/Downloads/DERA_Rohstoffinformationen/rohstoffinformationen-50-en.pdf?_blob=publicationFile&v=2.
[51] Klimenko VV, Ratner SV, Tereshin AG. Constraints imposed by key-material resources on renewable energy development, vol. 144. Renewable Sustainable Energy Rev.; Jul. 2021, 111011.
[52] Greim P, Solomon AA, Breyer C. Assessment of lithium criticality in the global energy transition and addressing policy gaps in transportation. Nat Commun Sep. 2020;11(1):4570.
[53] Zhou Y, et al. Dynamic criticality of by-products used in thin-film photovoltaic technologies by 2050. J Clean Prod Aug. 2020;263:121599.
[54] Climate-Smart Mining: Minerals for Climate Action,” World Bank. https://www.worldbank.org/en/topic/extractiveindustries/brief/climate-smart-mining-minerals-for-climate-action (accessed September 12, 2019).

[55] E. Rietveld, H. Boonman, T. Van Harmelen, and M. Hauck, "Global energy transition and metal demand." https://circulairemaakindustrie.nl/app/uploads/2020/06/TNO-2018-R11544-1.pdf (accessed February. 8, 2023).

[56] Ambrose H, Kendall A. Understanding the future of lithium: Part 1, resource model. J Ind Ecol Feb. 2020;24(1):80–9.

[57] Watari T, Nansai K, Nakajima K, McLellan BC, Dominish E, Giurco D. Integrating circular economy strategies with low-carbon scenarios: lithium use in electric vehicles. Environ Sci Technol Oct. 2019;53(20):11657–65.

[58] Watari T, McLellan BC, Giurco D, Dominish E, Yamasue E, Nansai K. Total material requirement for the global energy transition to 2050: a focus on transport and electricity. Resour Conserv Recycl Sep. 2019;148:91–103.

[59] Hache E, Seck GS, Simoen M, Bonnet C, Carcanague S. Critical raw materials and transportation sector electrification: a detailed bottom-up analysis in world transport. Appl Energy Apr. 2019;240:6–25.

[60] Dominish E, Teske S, Florin N. Responsible minerals sourcing for renewable energy. Institute for Sustainable Futures, University of Technology Sydney, Earthworks; 2019 [Online]. Available: https://earthworks.org/cms/assets/uploads/2019/04/MCEC_UTS_Report_lowres-1.pdf.

[61] Månberger A, Stenqvist B. Global metal flows in the renewable energy transition: exploring the effects of substitutes, technological mix and development. Energy Pol Aug. 2018;119:226–41.

[62] Ziemann S, Müller DB, Schebek L, Weil M. Modeling the potential impact of lithium recycling from EV batteries on lithium demand: a dynamic MFA approach. Resour Conserv Recycl Jun. 2018;133:76–85.

[63] Weil M, Ziemann S, Peters J. The issue of metal resources in Li-ion batteries for electric vehicles. In: Pistoia G, Liaw B, editors. Behaviour of lithium-ion batteries in electric vehicles: battery health, performance, safety, and cost. Cham: Springer International Publishing; 2018. p. 59–74.

[64] de Koning A, Kleijn R, Huppes G, Sprecher B, van Engelen G, Tukker A. Metal supply constraints for a low-carbon economy? Resour Conserv Recycl Feb. 2018;129:202–8.

[65] Harvey LDD. Resource implications of alternative strategies for achieving zero greenhouse gas emissions from light-duty vehicles by 2060. Appl Energy Feb. 2018;212:663–79.

[66] Zhou B, Li Z, Chen C. Global potential of rare earth resources and rare earth demand from clean technologies. Minerals Oct. 2017;7(11):203.

[67] Choi CH, Cao J, Zhao F. System dynamics modeling of indium material flows under wide deployment of clean energy technologies. Resour Conserv Recycl Nov. 2016;114:59–71.

[68] McLellan BC, Yamasue E, Tezuka T, Corder G, Golev A, Giurco D. Critical minerals and energy–impacts and limitations of moving to unconventional resources. Resources May 2016;5(2):19.

[69] Elshkaki A, Graedel TE. Solar cell metals and their hosts: a tale of oversupply and undersupply. Appl Energy Nov. 2015;158:167–77.

[70] Hoenderdaal S, Tercero Espinoza L, Marscheider-Weidemann F, Graus W. Can a dysprosium shortage threaten green energy technologies? Energy Jan. 2013;49:344–55.

[71] Zuser A, Rechberger H. Considerations of resource availability in technology development strategies: the case study of photovoltaics. Resour Conserv Recycl Nov. 2011;56(1):56–65.

[72] Elshkaki A. Long-term analysis of critical materials in future vehicles electrification in China and their national and global implications. Energy Jul. 2020;202:117697.

[73] Beylot A, Guyonnet D, Muller S, Vaxelaire S, Villeneuve J. Mineral raw material requirements and associated climate-change impacts of the French energy transition by 2050. J Clean Prod Jan. 2019;208:1198–205.

[74] Elshkaki A, Shen L. Energy-material nexus: the impacts of national and international energy scenarios on critical metals use in China up to 2050 and their global implications. Energy Aug. 2019;180:903–17.

[75] Fishman T, Graedel TE. Impact of the establishment of US offshore wind power on neodymium flows. Nat Sustain Mar. 2019;2(4):332–8.

[76] Ciacci L, Vassura I, Cao Z, Liu G, Passarini F. Recovering the 'new twin': analysis of secondary neodymium sources and recycling potentials in Europe. Resour Conserv Recycl Mar. 2019;142:143–52.

[77] Simon B, Ziemann S, Weil M. Potential metal requirement of active materials in lithium-ion battery cells of electric vehicles and its impact on reserves: focus on Europe. Resour Conserv Recycl Nov. 2015;104:300–10.

[78] Cao Z, et al. Resourcing the fairytale country with wind power: a dynamic material flow analysis. Environ Sci Technol Oct. 2019;53(19):11313–22.

[79] Arent D, et al. Implications of high renewable electricity penetration in the U.S. for water use, greenhouse gas emissions, land-use, and materials supply. Appl Energy Jun. 2014;123:368–77.

[80] Nassar NT, Wilburn DR, Goonan TG. Byproduct metal requirements for U.S. wind and solar photovoltaic electricity generation up to the year 2040 under various Clean Power Plan scenarios. Appl Energy Dec. 2016;183:1209–26.

[81] Miyamoto W, Kosai S, Hashimoto S. Evaluating metal criticality for low-carbon power generation technologies in Japan. Minerals Feb. 2019;9(2):95.

[82] JRC:Joint Research Centre. Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised energy system. Publications Office of the European Union; 2020.

[83] Lee J, Bazilian M, Hastings-Simon S. The material foundations of a low-carbon economy. One Earth Mar. 2021;4(3):331–4.

[84] Xu C, Dai Q, Gaines L, Hu M, Tukker A, Steubing B. Future material demand for automotive lithium-based batteries. Communications Materials Dec. 2020;1(1):1–10.

[85] Lithium Statistics, Information. https://www.usgs.gov/centers/national-minerals-information-center/lithium-statistics-and-information. Nov. 05, 2022.

[86] Tilton JE, et al. Public policy and future mineral supplies. Resour Pol Aug. 2018;57:55–60.

[87] "Energy Technology Perspectives 2017," IEA. https://www.iea.org/data-and-statistics/data-product/energy-technology-perspectives-2017-2 (accessed Nov. 08, 2022).

[88] Crystalline Silicon Photovoltaics Research," Energy.gov. https://www.energy.gov/eere/solar/crystalline-silicon-photovoltaics-research (accessed Feb. 09, 2023).

[89] P. Bojek, "Solar PV," IEA. https://www.iea.org/reports/solar-pv (accessed Feb. 09, 2023).

[90] United Nations Environment Programme and International Resource Panel. Recycling rates of metals: a status report. 2011.

[91] Ziegler MS, Trancik JE. Re-examining rates of lithium-ion battery technology improvement and cost decline. Energy Environ Sci Apr. 2021;14(4):1635–51.

[92] Ziegler MS, Song J, Trancik JE. Determinants of lithium-ion battery technology cost decline. Energy Environ Sci Dec. 2021;14(12):6074–98.

[93] Kavlak G, McNerney J, Trancik JE. Evaluating the causes of cost reduction in photovoltaic modules. Energy Pol Dec. 2018;123:700–10.

[94] Critical minerals threaten a decades-long trend of cost declines for clean energy technologies," IEA. https://www.iea.org/commentaries/critical-minerals-threaten-a-decades-long-trend-of-cost-declines-for-clean-energy-technologies (accessed Nov. 28, 2022).